Amplitude analysis of photo-/electroproduction data in the resonance region

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Useful Links

- SPIRES
- PDG Homepage
- Durham Data Base
- Bonn Homepage

CB-ELSA Homepage

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Last changes: January 26th, 2010.

Energy dependent fully covariant approach

In many cases an unambiguous partial wave decomposition at fixed energies is impossible. Then the energy and angular parts should be analyzed together:

$$A(s,t) \;=\; \sum_{\beta\beta' n} A_n^{\beta\beta'}(s) Q^{(\beta)+}_{\mu_1\ldots\mu_n} F^{\mu_1\ldots\mu_n}_{\nu_1\ldots\nu_n} Q^{(\beta')}_{\nu_1\ldots\nu_n}$$

πN **interaction:**

$$Q^{(+n)}_{\mu_1\ldots\mu_n} = X^{(n)}_{\mu_1\ldots\mu_n} \qquad\qquad Q^{(-n)}_{\mu_1\ldots\mu_n} = i\gamma_\nu\gamma_5 X^{(n+1)}_{\nu\mu_1\ldots\mu_n}$$

$$X^0 = 1\,; \quad X^1_\mu = k^\perp_\mu\,; \quad X^2_{\mu\nu} = \frac{3}{2}\left(k^\perp_\mu k^\perp_\nu - \frac{1}{3}\,k^2_\perp g^\perp_{\mu\nu}\right);$$

$$X^3_{\mu\nu\alpha} = \frac{5}{2}\left[k^\perp_\mu k^\perp_\nu k^\perp_\alpha - \frac{k^2_\perp}{5}\left(g^\perp_{\mu\nu}k^\perp_\alpha + g^\perp_{\mu\alpha}k^\perp_\nu + g_{\nu\alpha}k^\perp_\mu\right)\right],$$

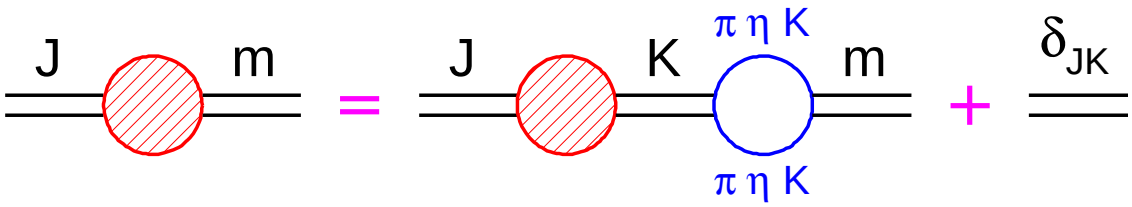
1. C. Zemach, Phys. Rev. 140, B97 (1965); 140, B109 (1965).

2. S.U.Chung, Phys. Rev. D 57, 431 (1998).

A. V. Anisovich, V. V. Anisovich, V. N. Markov, M. A. Matveev and A. V. Sarantsev, J. Phys. G 28, 15 (2002)

3. B. S. Zou and D. V. Bugg, Eur. Phys. J. A 16, 537 (2003)

N/D based (D-matrix) analysis of the data



$$D_{jm} = D_{jk} \sum_{\alpha} B_{\alpha}^{km}(s) \frac{1}{M_m - s} + \frac{\delta_{jm}}{M_j^2 - s} \qquad \hat{D} = \hat{\kappa}(I - \hat{B}\hat{\kappa})^{-1}$$

$$\hat{\kappa} = diag\left(\frac{1}{M_1^2 - s}, \frac{1}{M_2^2 - s}, \ldots, \frac{1}{M_N^2 - s}, R_1, R_2 \ldots\right)$$

$$\hat{B}_{ij} = \sum_{\alpha} B_{\alpha}^{ij} = \sum_{\alpha} \int \frac{ds'}{\pi} \frac{g_{\alpha}^{(R)i} \rho_{\alpha}(s', m_{1\alpha}, m_{2\alpha}) g_{\alpha}^{(L)j}}{s' - s - i0}$$

Channels included in D-matrix: $\pi N, \eta N, K\Lambda, K\Sigma, \Delta\pi$**,** $N\sigma, N\rho(770)$**,** $N(1520)\pi$**,** $N(1535)\pi$**,** $N\omega$**, Black Box**

Minimization methods

1. **The two body final states $\pi N, \gamma N \to \pi N, \eta N, K\Lambda, K\Sigma, \omega N, K^*\Lambda$: χ^2 method.**

   For n measured bins we minimize

$$\chi^2 = \sum_j^n \frac{(\sigma_j(PWA) - \sigma_j(exp))^2}{(\Delta\sigma_j(exp))^2}$$

   Present solution for γp reaction $\chi^2 = 69435$ for 46644 points. $\chi^2/N_F = 1.49$

2. **Reactions with three or more final states are analyzed with logarithm likelihood method. $\pi N, \gamma N \to \pi\pi N, \pi\eta N$. The minimization function:**

$$f = -\sum_j^{N(data)} ln \frac{\sigma_j(PWA)}{\sum_m^{N(rec\,MC)} \sigma_m(PWA)}$$

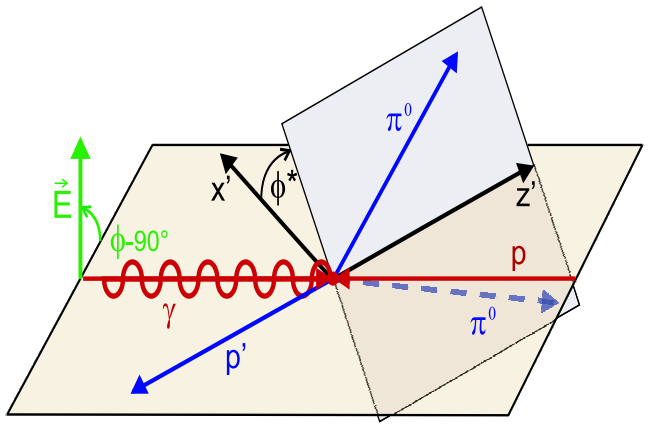
   This method allows us to take into account all correlations in many dimensional phase space. Above 1 000 000 data events are taken in the fit.

The included meson photoproduction data

DATA	2011-2019	added in 2019-2022
$\pi N \to \pi N$ **ampl.**	**SAID**	**Hoehler (energy fixed)**
$\pi^- p \to \pi\pi N$	$d\sigma/d\Omega$ ($\pi^0\pi^0 n$, $\pi^+\pi^- n$,$\pi^-\pi^0 p$)	
$\pi^- p \to \eta n$	$d\sigma/d\Omega$	
$\pi p \to K\Lambda, K\Sigma$	$d\sigma/d\Omega$, P,β	
$\pi p \to \omega n$		$d\sigma/d\Omega$
$\gamma p \to \pi N$	$d\sigma/d\Omega, \Sigma, T, P, E, G, H$ ($\pi^0 p, \pi^+ n$)	
$\gamma p \to \eta p$	$d\sigma/d\Omega$,Σ, F, T, P, H, G, E	
$\gamma p \to \eta' p$	$d\sigma/d\Omega$, Σ	
$\gamma p \to K\Lambda$, $K\Sigma$	$d\sigma/d\Omega$, $\Sigma, P, T, C_x, C_z, O_{x'}, O_{z'}, T_x, T_z$	
$\gamma p \to \pi^0\pi^0 p$	$d\sigma/d\Omega, \Sigma, E, I_c, I_s$	$\Sigma, E, T, P, H, F, P_x, P_y$ **(CB-ELSA)**
$\gamma p \to \pi^+\pi^- p$	$d\sigma/d\Omega$	I_c, I_s **(CLAS)**
$\gamma p \to \omega p$	$d\sigma/d\Omega, \Sigma, \rho^k_{ij}, E, G$ **(CB-ELSA)**, Σ, **P,T,F,H (CLAS)**	**Taken explicitly**
$\gamma n \to \Lambda K, \Sigma^- K$	$d\sigma/d\Omega$ **(CLAS), E (CLAS)**	Σ, **G (CLAS)**
$\gamma n \to \pi^- p$	$d\sigma/d\Omega$,Σ, P, E, Σ **(CLAS)**	
$\gamma n \to \eta n$	$d\sigma/d\Omega$ **(CB-ELSA, MAMI)**,Σ, $d\sigma/d\Omega$ $(h = \frac{1}{2})$ **(CB-ELSA)**	

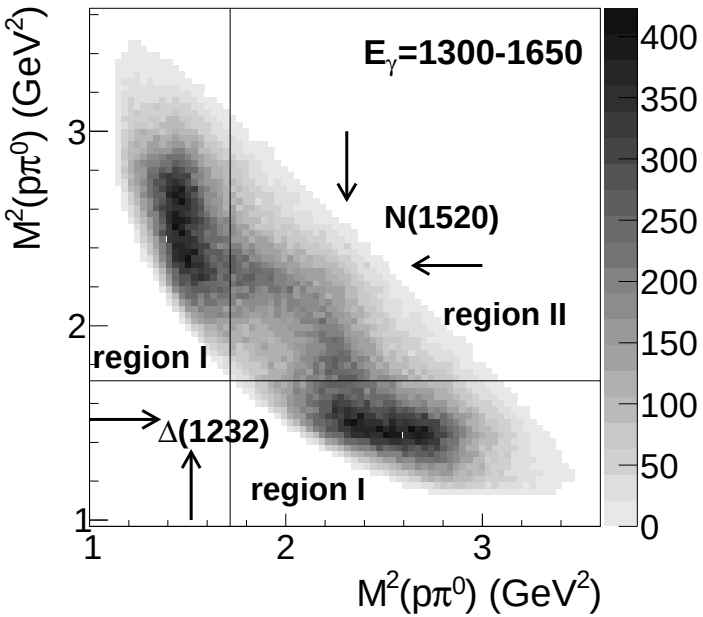
$\gamma p \to \pi^0\pi^0 p$ Polarization observables

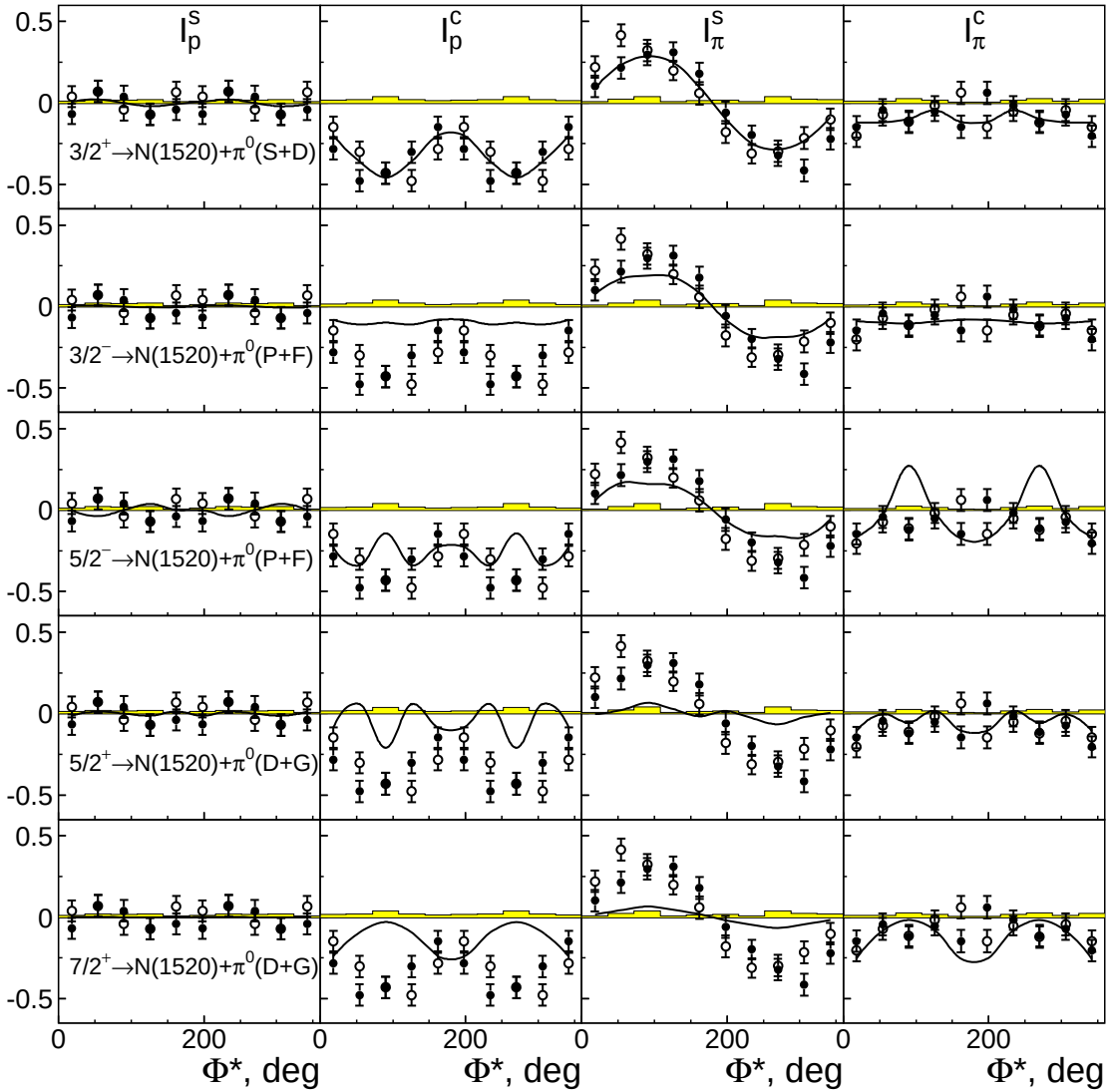
$$\frac{d\sigma}{d\Omega}(\Theta,\varphi) = \frac{d\sigma_0}{d\Omega}(\Theta)\left[1 - \Sigma(\Theta)\cos(2\varphi) - \Lambda_x H(\Theta)\sin(2\phi) - \Lambda_y P(\Theta)\cos(2\varphi) + \Lambda_y T(\Theta)\right]$$



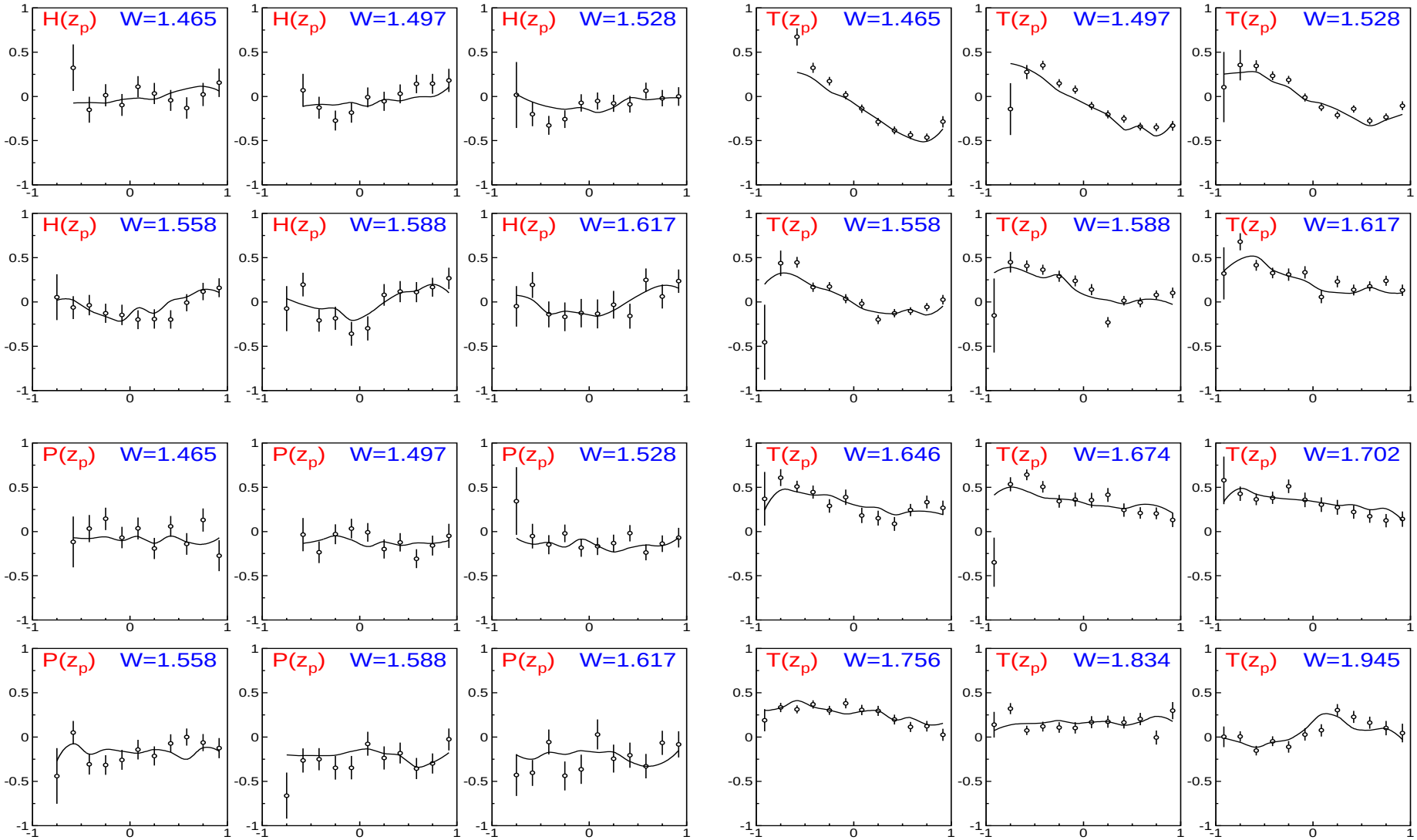
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(\Theta)\Big[1 + \Lambda_x P_x + \Lambda_y P_y \quad + \sin(2\varphi)\big(I^s + \Lambda_x P_x^s + \Lambda_y P_y^s\big)$$
$$+ \cos(2\varphi)\big(I^c + \Lambda_x P_x^c + \Lambda_y P_y^c\big)\Big]$$

I_c and I_s polarization data are very important for the partial wave analysis

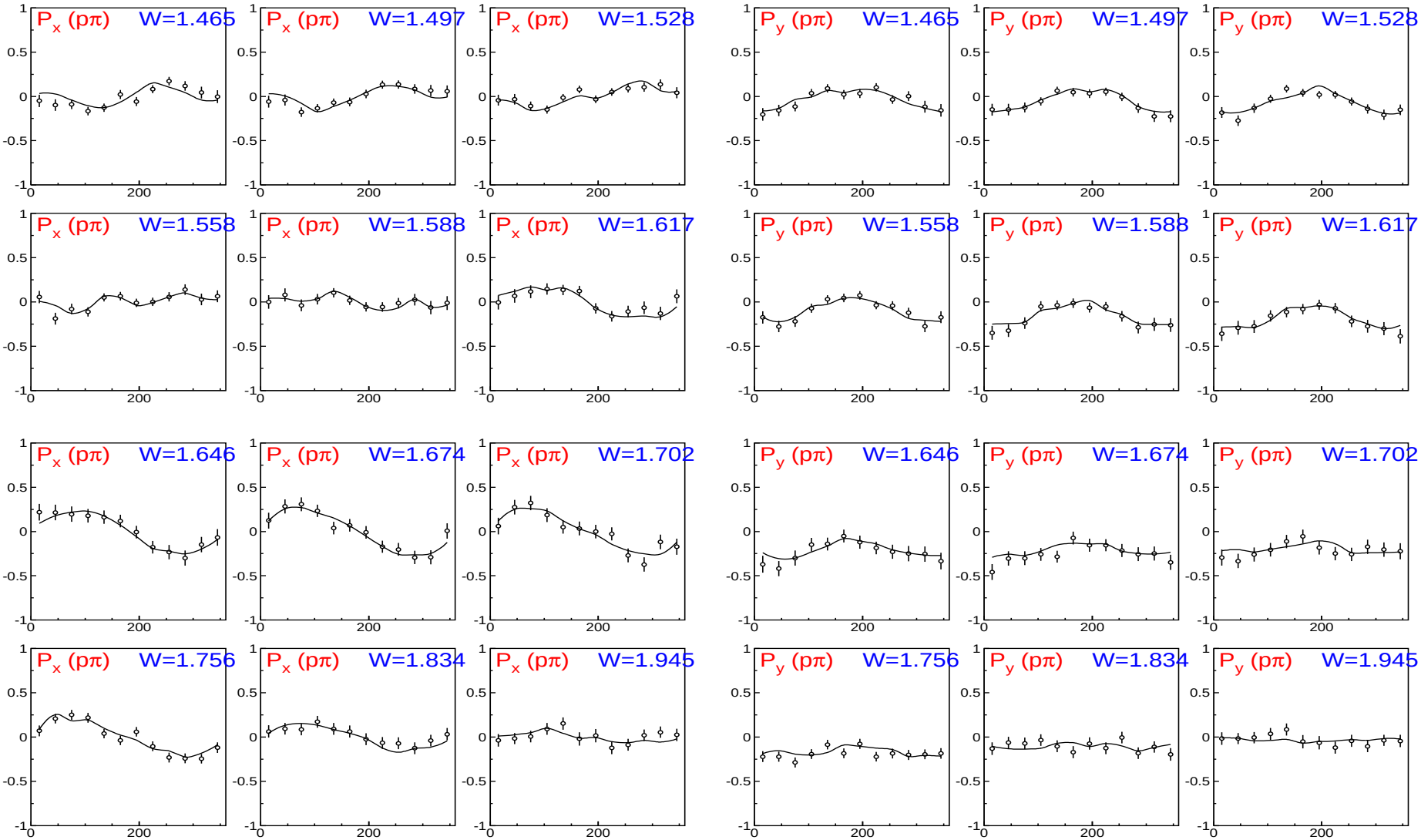




$\gamma p \to \pi^0 \pi^0 p$ polarization observables from CB-ELSA (T.Seifen)

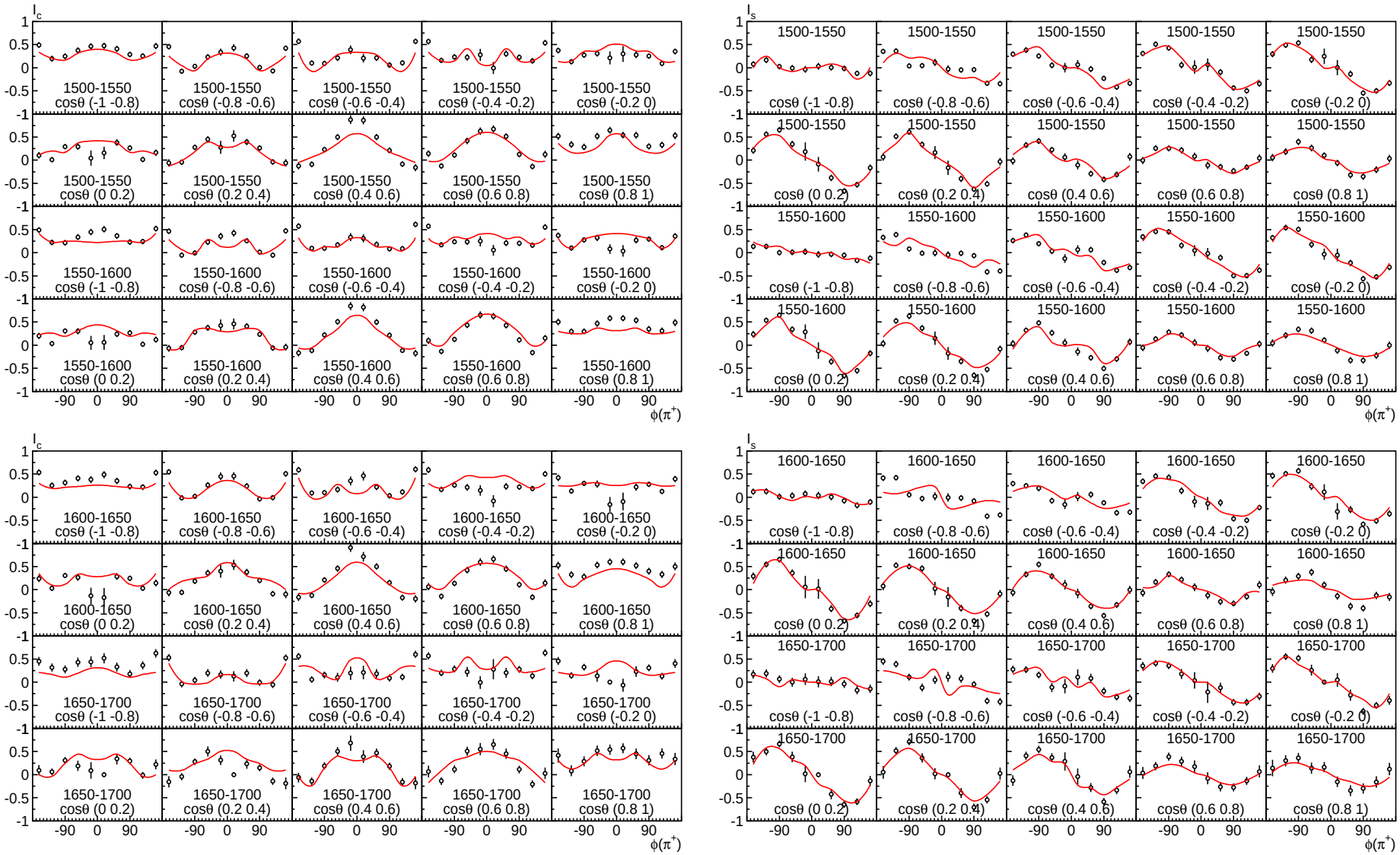


$\gamma p \to \pi^0\pi^0 p$ polarization observables from CB-ELSA (T.Seifen)



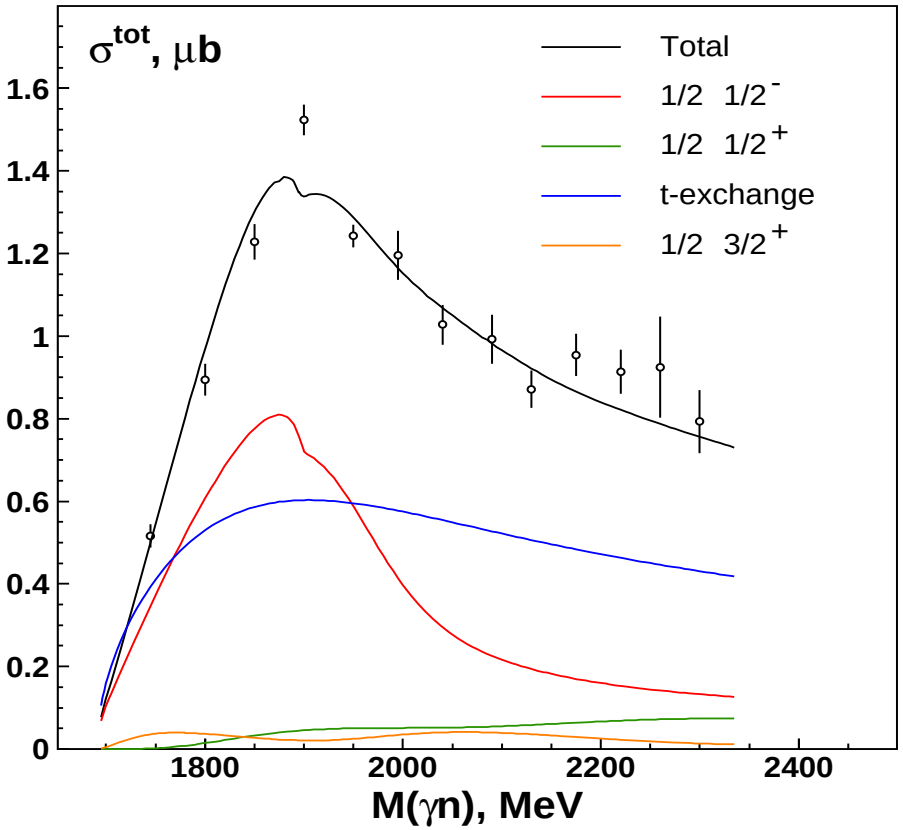
$\gamma p \to \pi^+\pi^- p$: I^c and I^c polarization observables from CLAS (V.Crede)

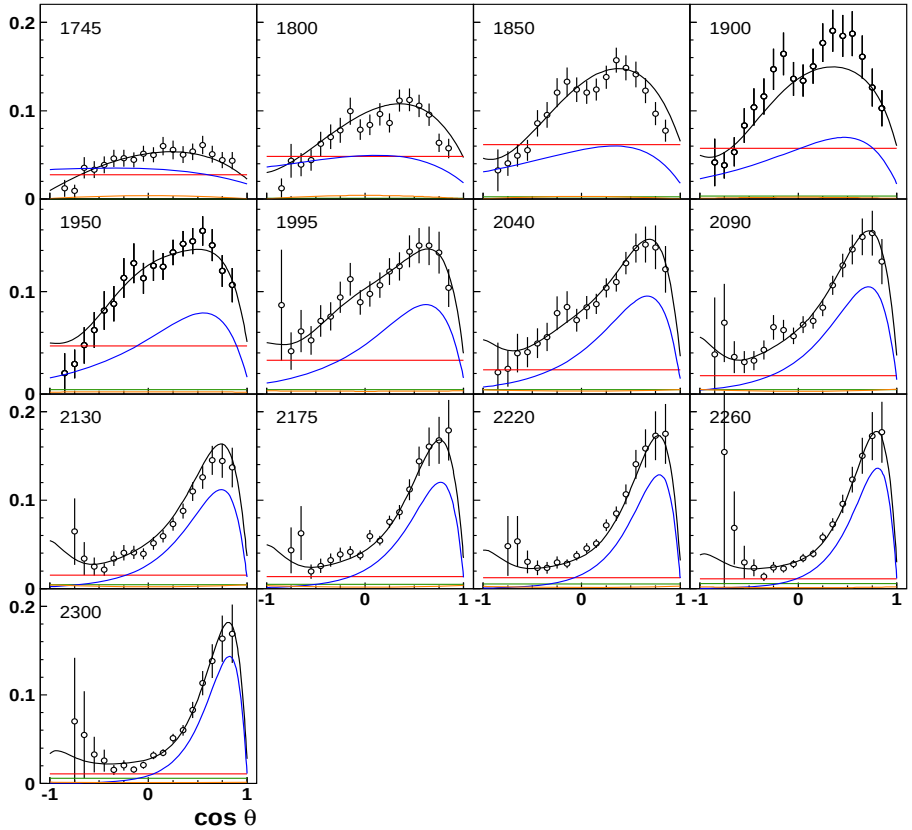
I^c I^s



	Nπ	$\Delta\pi$ $(L < J)$	$\Delta\pi$ $(L > J)$	N$(1440)\pi$	N$(1520)\pi$	N$(1535)\pi$	Nσ
N$(1535)\,1/2^-$	46±5 52±5	x	5±3 2.5±1.5	6±5 12±8	- -	- -	4±2 6±4
N$(1520)\,3/2^-$	61±3 61±2	10±4 19±4	10±3 9±2	$<$1 $<$1	- -	- -	$<$2 < 2
N$(1650)\,1/2^-$	48±4 51±4	x	6±3 12±6	5±3 16±10	- -	- -	3±2 10±8
N$(1700)\,3/2^-$	20±8 15±6	66±17 65±15	7±4 9±5	9±5 7±4	$<$2 $<$4	$<$1 $<$1	6±4 8±6
N$(1675)\,5/2^-$	40±1 41±2	19±3 30±7	- -	- -	- -	- -	1±1 5±2
$\Delta(1620)\,1/2^-$	30±5 28±3	x	28±15 62±10	15±8 6±3	- -	- -	x
$\Delta(1700)\,3/2^-$	22±6 22±4	16±15 20±15	8±6 10±6	3±2 $<$1	$<$1 3±2	$<$1 $<$1	x
$\Delta(1600)\,3/2^+$	17±4 14±4	70±6 77±5	$<$2 $<$2	$<$1 22±5	- -	- -	x
N$(1720)\,3/2^+$	13±5 11±4	15±7 62±15	6±6 6±6	6±5 $<$2	7±3 3±2	4±2 $<$2	20±10 2 8±6
N$(1680)\,5/2^+$	68±8 62±4	8±4 7±3	8±4 10±3	- -	$<$1 $<$1	- -	8±4 2 14±5
$\Delta(1910)\,1/2^+$	16±6 12±3	x	17±9 50±16	50±18 6±3	- -	4±2 5±3	x
$\Delta(1920)\,3/2^+$	12±6 8±4	5±4 18±10	40±20 58±14	9±6 < 4	10±8 < 5	5±5 < 2	x
$\Delta(1905)\,5/2^+$	13±4 13±2	20±12 33±10	- -	- -	- -	< 1 < 1	x
$\Delta(1950)\,7/2^+$	46±4 46±2	5±4 5±4	- -	- -	- -	- -	x

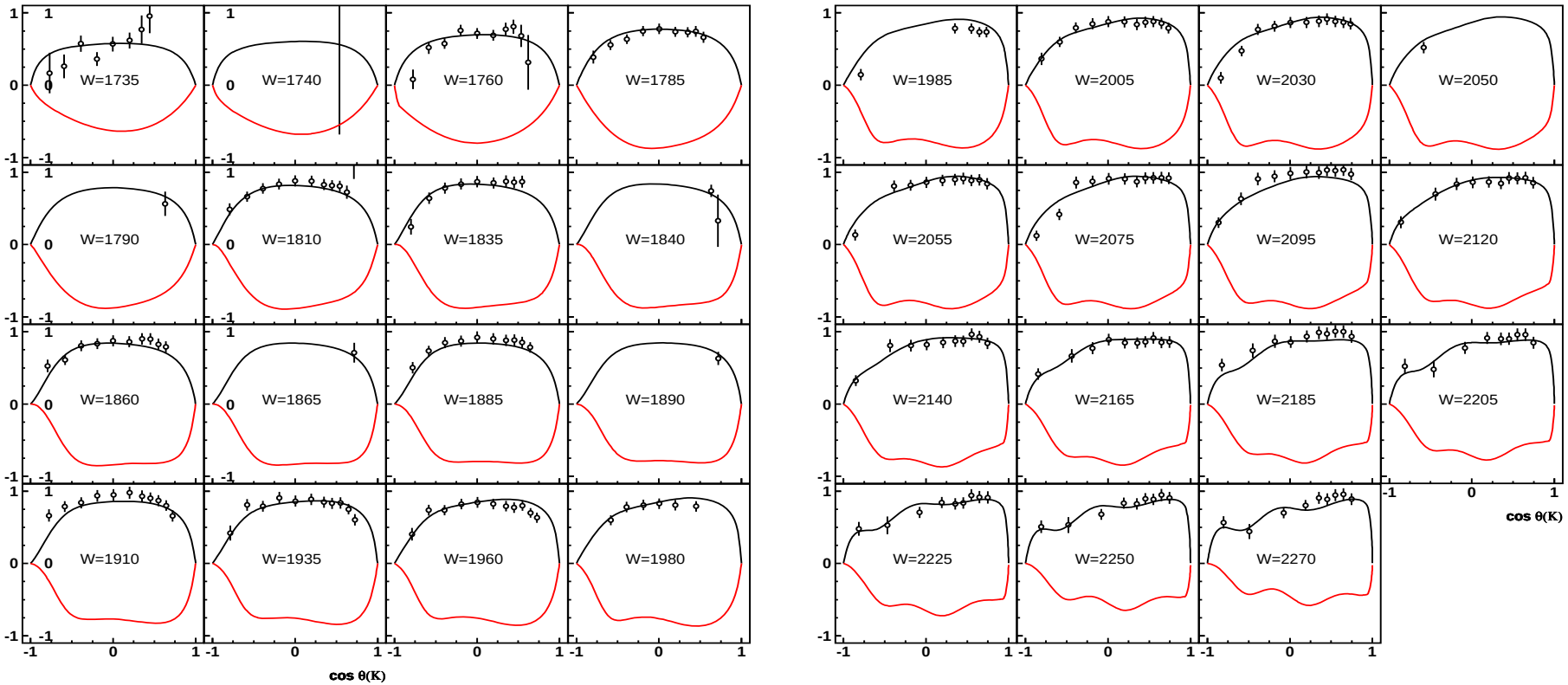
The $\gamma n \to K^+\Sigma^-$ photoproduction data (included in BG2019)





The beam asymmetry for the $\gamma n \to K^+\Sigma^-$ data

N. Zachariou *et al.* [CLAS], Phys. Lett. B 827, 136985 (2022).

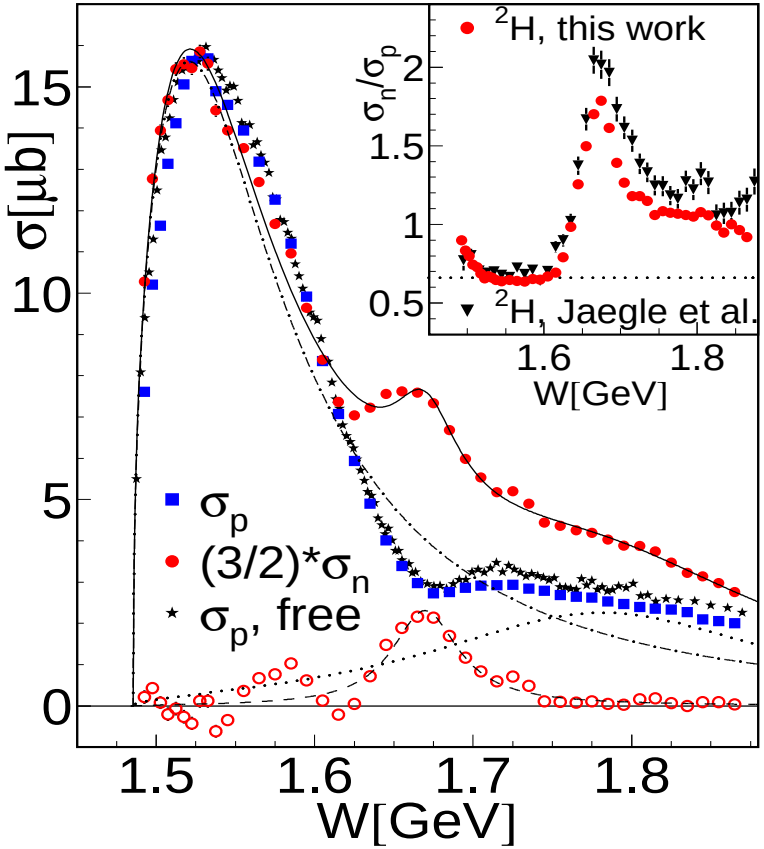


BG2019 **BG2022**

The data fix the γn couplings for the $N^*(3/2^+)$ states. For $N(1900)3/2^+$ the helicity couplings changed the sign.

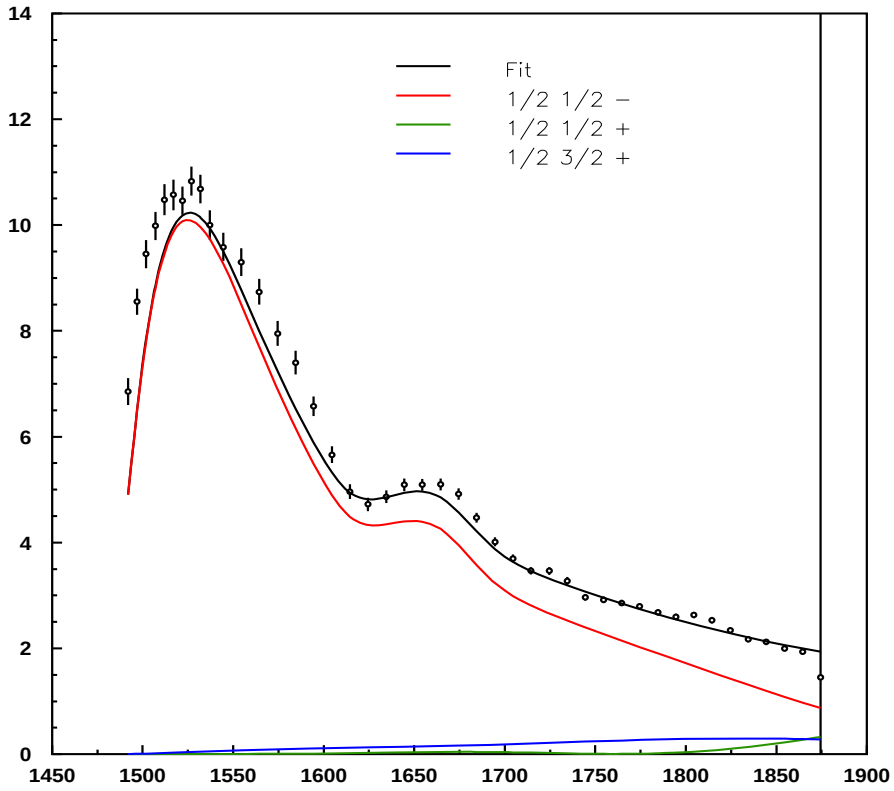
The search for the pentaquark P_{11} state

In memory of Bernd Krusche

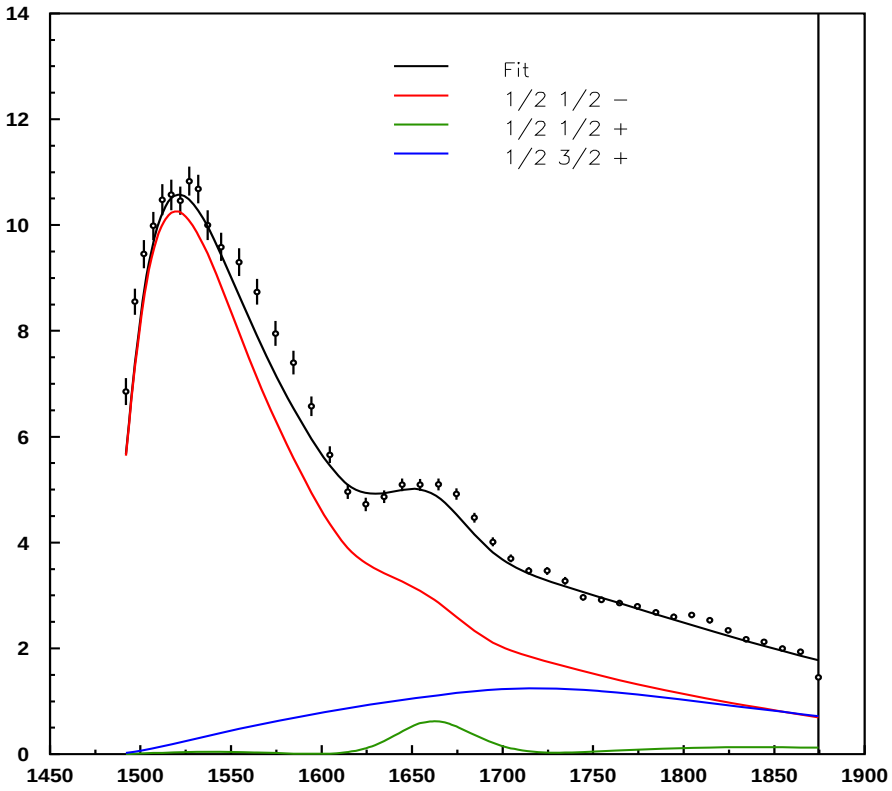


The fit of the $\gamma n \to \eta n$ data with BG2022

D. Werthmüller *et al.* [A2 Collaboration], Phys. Rev. Lett. 111, 232001 (2013)



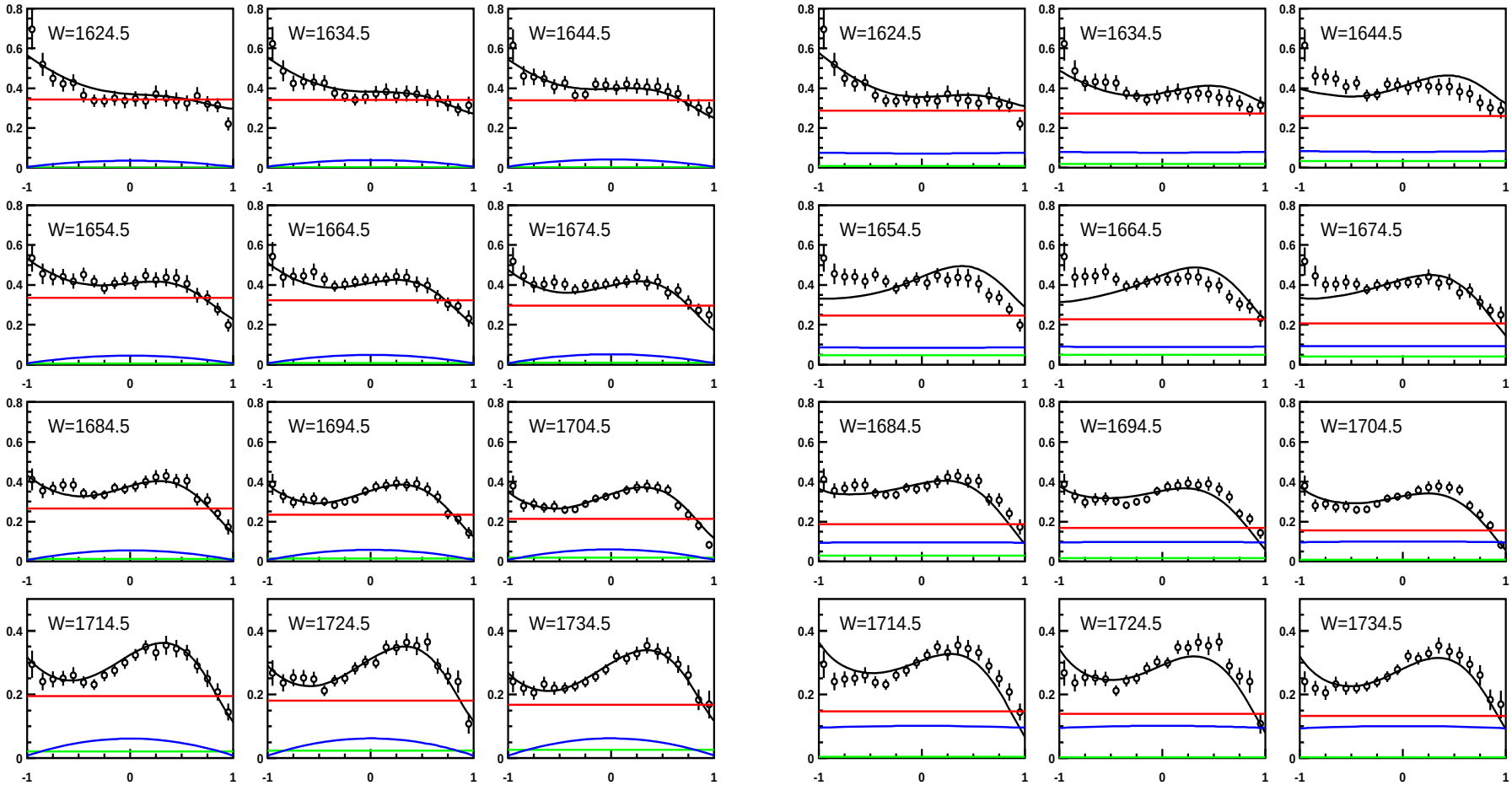
No narrow P_{11}



$P_{11}(1680)$

The fit of the $\gamma n \to \eta n$ data with BG2022

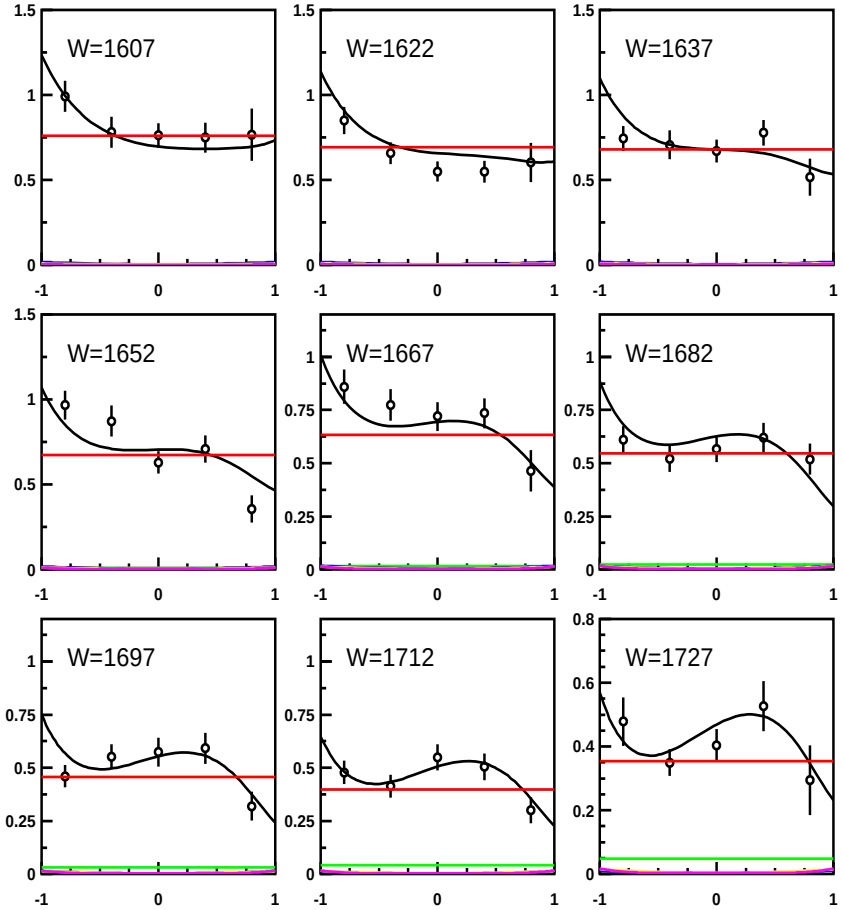
D. Werthmüller *et al.* [A2 Collaboration], Phys. Rev. Lett. 111, 232001 (2013)



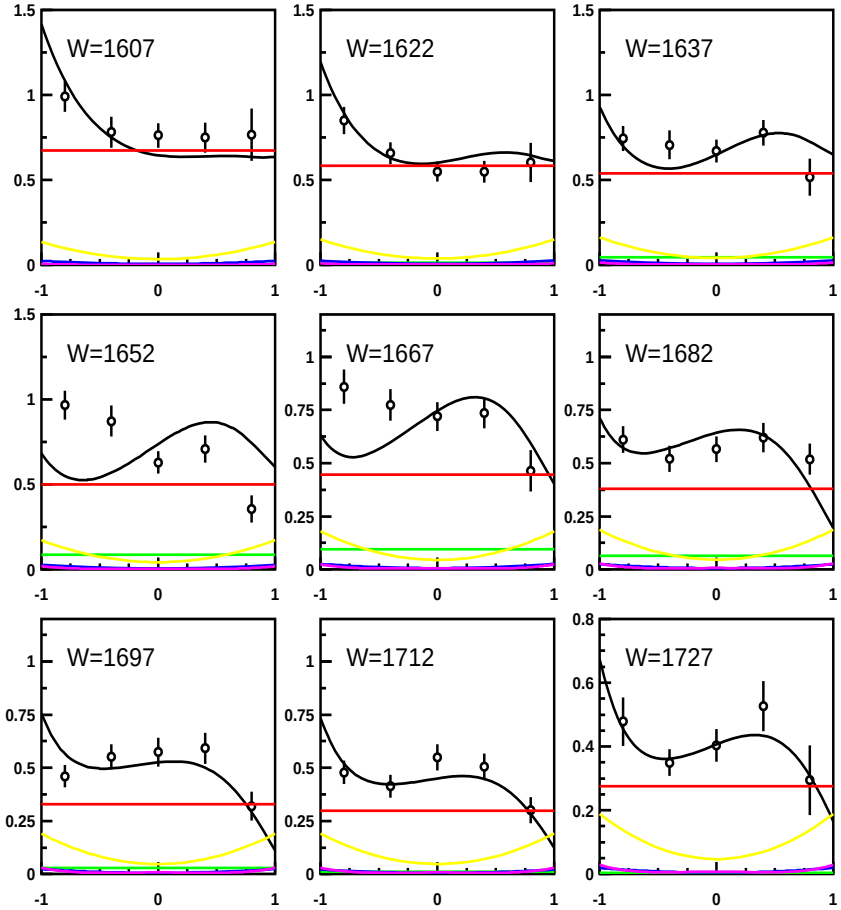
No narrow P_{11} $P_{11}(1680)$

The helicity 1/2 $\gamma n \to \eta n$ data with BG2022

L. Witthauer *et al.*, Phys. Rev. Lett. 117, no. 13, 132502 (2016)

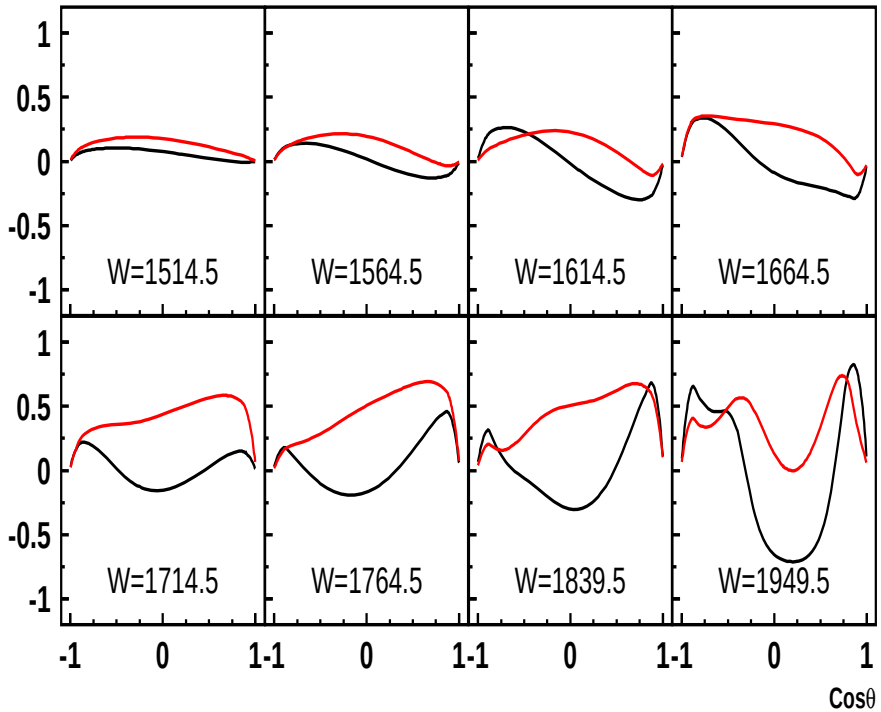


No narrow P_{11}

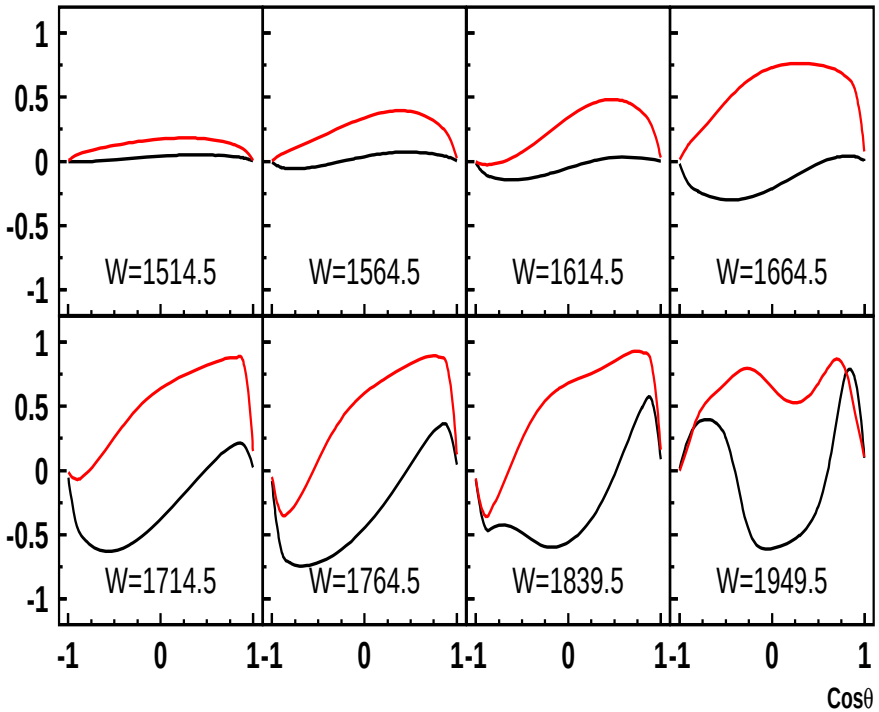


$P_{11}(1680)$

Prediction for the T and P observables

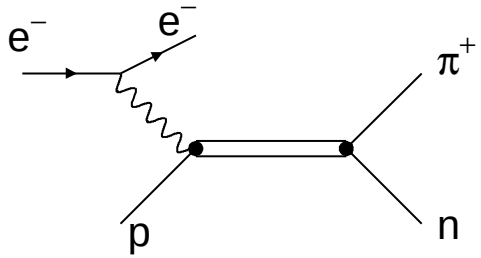


Interference S_{11} states



$P_{11}(1680)$

Electro-production of pseudoscalar mesons



$$A = \omega^* J_\mu \omega' \bar{u}(k_f)\gamma_\mu u(k_i)\frac{e}{q^2}$$

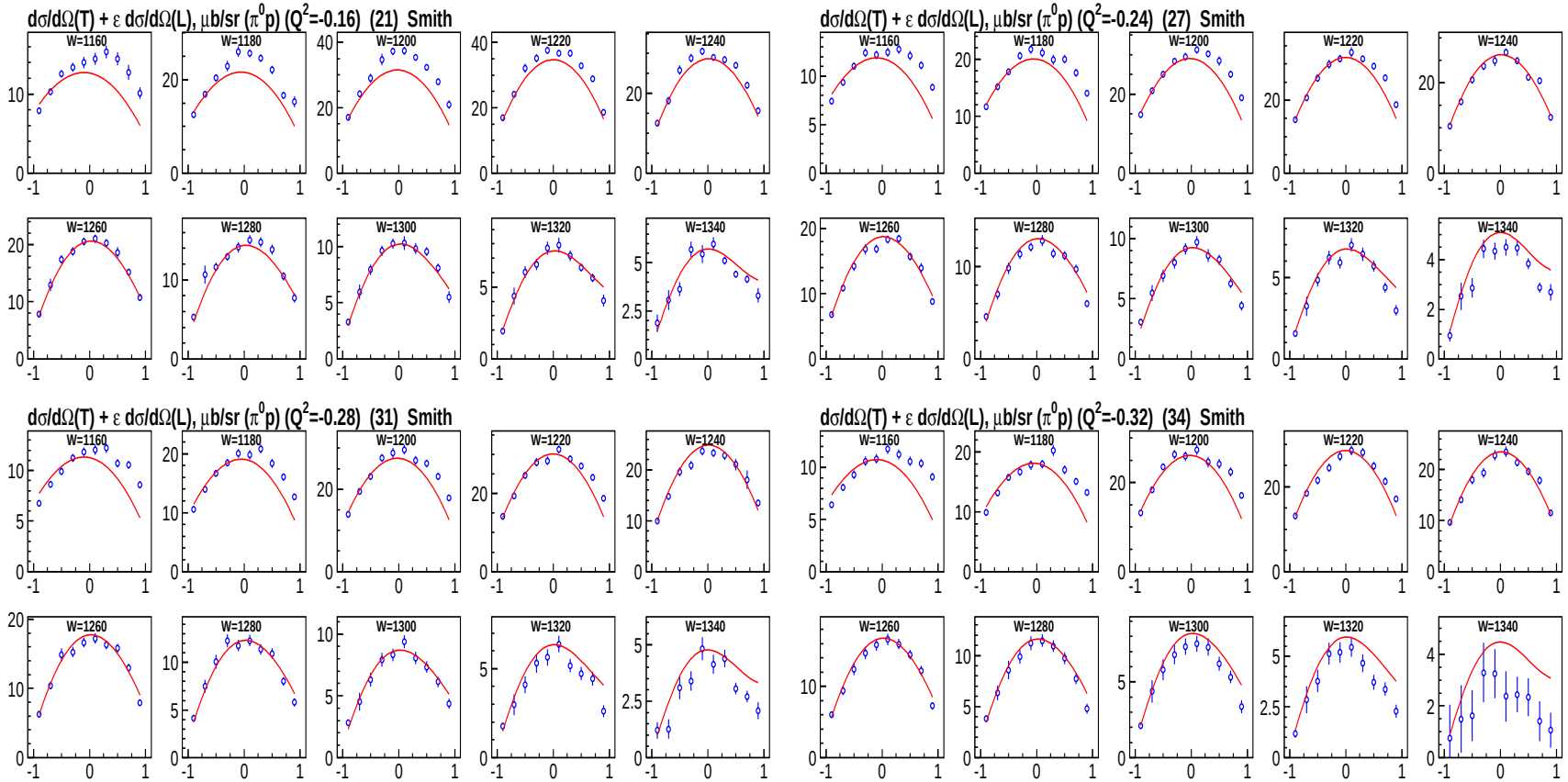
$$|A|^2 = J_\mu J_\nu^* \frac{e^2}{2Q^4}\left(2K_\mu K_\nu + \frac{q^2}{2}g_{\mu\nu} - \frac{1}{2}q_\mu q_\nu + ih\varepsilon_{\mu\nu\alpha\beta}q_\alpha K_\beta\right)$$

$$\frac{d\sigma}{d\Omega_f d\varepsilon_f d\Omega_\pi} = \Gamma\frac{d\sigma_v}{d\Omega_\pi} \qquad \Gamma = \frac{\alpha}{2\pi^2}\frac{\varepsilon_f}{\varepsilon_i}\frac{|k_\gamma|}{Q^2}\frac{1}{1-\varepsilon}$$

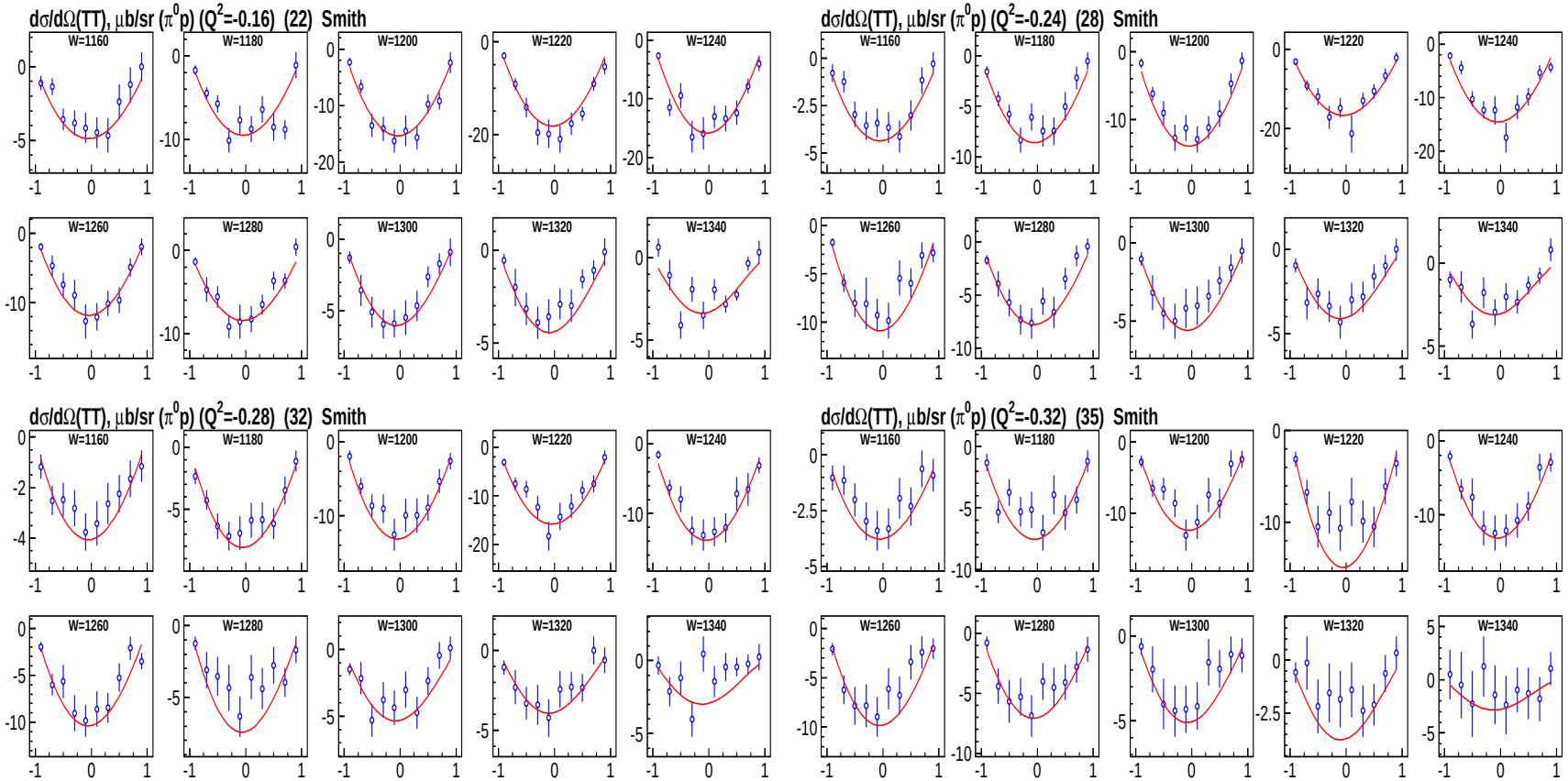
$$\begin{aligned}\frac{d\sigma_v}{d\Omega_\pi} &= \frac{d\sigma_T}{d\Omega_\pi} + \varepsilon_L\frac{d\sigma_L}{d\Omega_\pi} + \left[2\varepsilon_L(1+\varepsilon)\right]^{\frac{1}{2}}\frac{d\sigma_{TL}}{d\Omega_\pi}\cos\Phi_\pi + \varepsilon\frac{d\sigma_{TT}}{d\Omega_\pi}\cos 2\Phi_\pi \\ &+ h\left[2\varepsilon_L(1-\varepsilon)\right]^{\frac{1}{2}}\frac{d\sigma_{TL'}}{d\Omega_\pi} + h(1-\varepsilon^2)^{\frac{1}{2}}\frac{d\sigma_{TT'}}{d\Omega_\pi}\end{aligned}$$

$\varepsilon_i, k_i, \varepsilon_f, k_f$ **- momenta of the initial and final electrons (**$K = \frac{1}{2}(k_i + k_f)$**).** $\vec{q}$ **and** Θ_e **are evaluated in the lab. frame. h is the helicity of the incoming electron. Amaldi et a1 1979, Donnachie and Shaw 1978**

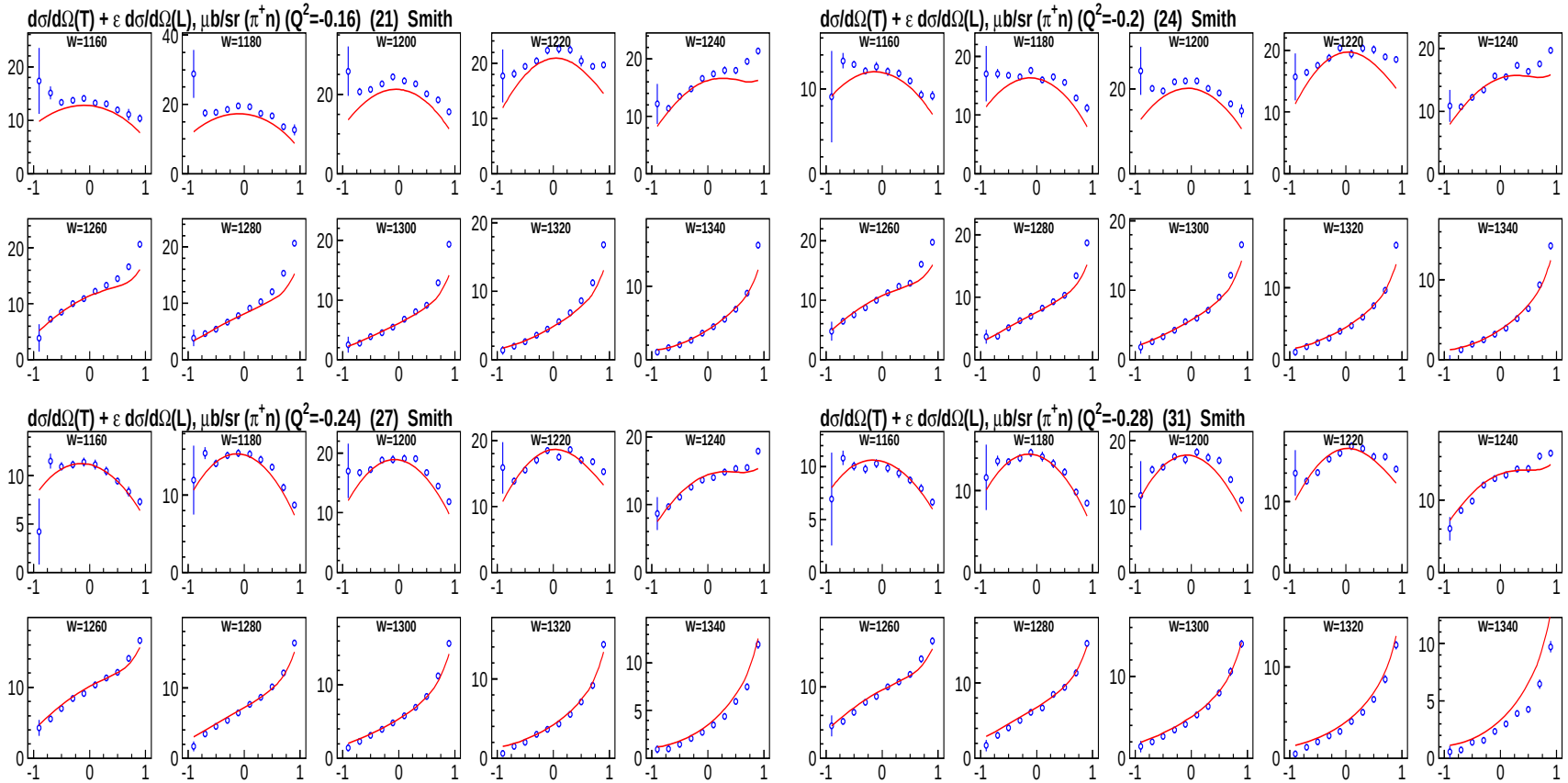
The description of the $\gamma^* p \to \pi^0 p$ data



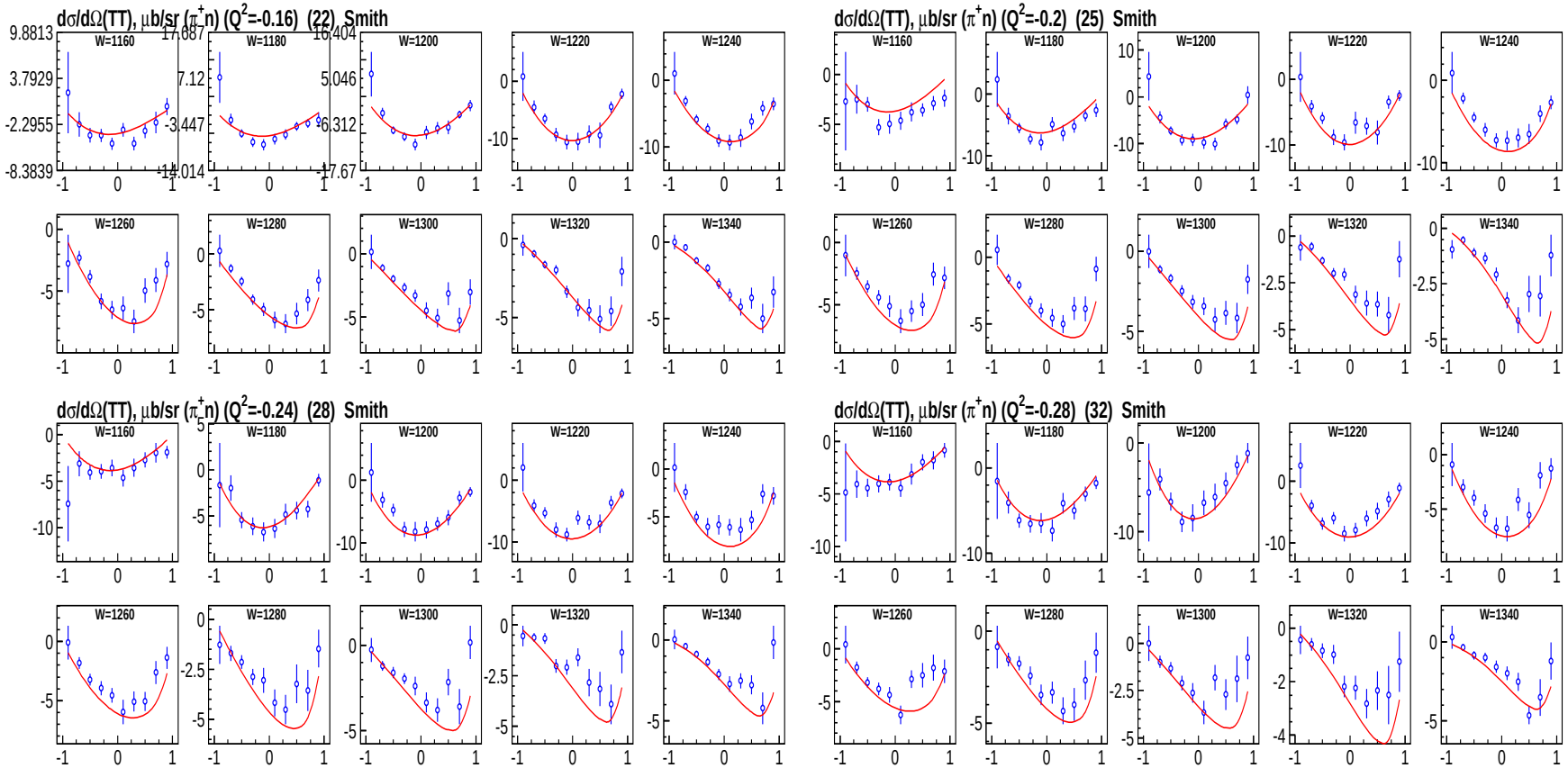
The description of the $\gamma^* p \to \pi^0 p$ data



The description of the $\gamma^* p \to \pi^+ n$ data

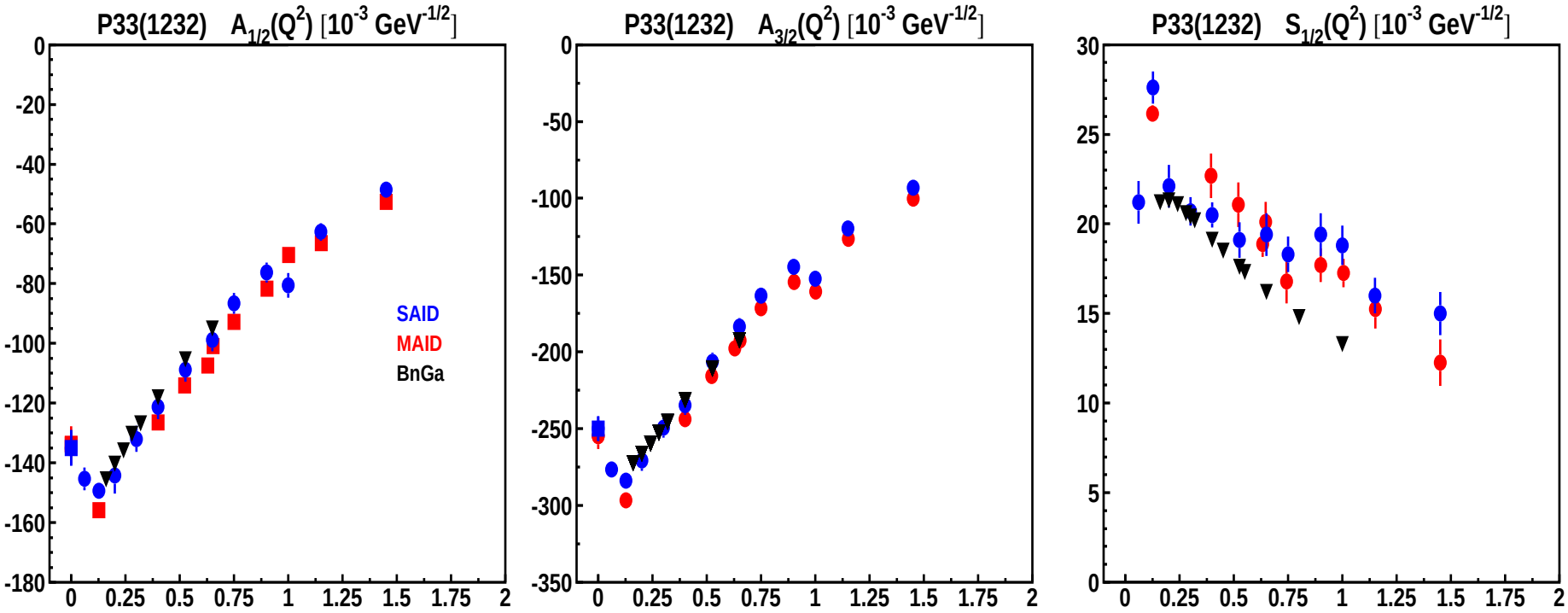


The description of the $\gamma^* p \to \pi^+ n$ data



The form factors for the $P_{33}(1232)$ state

(Very Preliminary)



SUMMARY

- **The new BG2022-02 solution, which describes 198 data sets is obtained.**
- **The new polarization data on the double pion photoproduction provide an important constrain for the data analysis.**
- **The branching ratios of the baryon states into $\Delta\pi$, $N\sigma$, $N(1440)\pi$, $N(1520)\pi$, $N(1535)\pi$ and $N(1680)\pi$ decay channels are determined with a good precision.**
- **The new data on the beam asymmetry on the $\gamma n \to K^+\Sigma^-$ fix the γn couplings of the $N(3/2^+)$ states.**
- **The new solution confirms that the bump in the mass region of 1620-1720 MeV is due to interference of the S_{11} states.**
- **The combined analysis of the all single meson electro-production data in the progress. The first results are obtained. But the description of the data should be improved.**

Resonance	Rating	N_{pp}	Resonance	Rating	N_{pp}	Resonance	Rating	N_{pp}
$N(1440)1/2^+$	****	13	$N(1520)3/2^-$	****	17	$N(1535)1/2^-$	****	15
$N(1650)1/2^-$	****	18	$N(1675)5/2^-$	****	14	$N(1680)5/2^+$	****	17
$N(1685)$	*		$N(1700)3/2^-$	***	15	$N(1710)1/2^+$	***	14
$N(1720)3/2^+$	****	17	$N(1860)5/2^+$	**	9	$N(1875)3/2^-$	***	16
$N(1880)1/2^+$	***	20	$N(1895)1/2^-$	****	17	$N(1900)3/2^+$	****	18
$N(1990)7/2^+$	**	9	$N(2000)5/2^+$	**	11	$N(2040)3/2^+$	*	
$N(2060)5/2^-$	**	13	$N(2100)1/2^+$	*		$N(2150)3/2^-$	**	11
$N(2190)7/2^-$	****	11	$N(2220)7/2^-$	****	7	$N(2250)9/2^-$	****	
$N(2600)11/2^-$	***		$N(2700)13/2^+$	**				
$\Delta(1232)$	****	8	$\Delta(1600)3/2^+$	***	12	$\Delta(1620)1/2^-$	****	10
$\Delta(1700)3/2^-$	****	11	$\Delta(1750)1/2^+$	*		$\Delta(1900)1/2^-$	**	13
$\Delta(1905)5/2^+$	****	11	$\Delta(1910)1/2^+$	****	13	$\Delta(1920)3/2^+$	***	21
$\Delta(1930)5/2^-$	***		$\Delta(1940)3/2^-$	*	5	$\Delta(1950)7/2^+$	****	13
$\Delta(2000)5/2^+$	**		$\Delta(2150)1/2^-$	*		$\Delta(2200)7/2^-$	*	
$\Delta(2300)9/2^+$	**		$\Delta(2350)3/2^-$	*		$\Delta(2390)7/2^+$	*	
$\Delta(2420)11/2^+$	****		$\Delta(2400)9/2^-$	****		$\Delta(2750)13/2^-$	**	
$\Delta(2950)15/2^+$	**							